Stopper rod tilt and effect on nozzle flow

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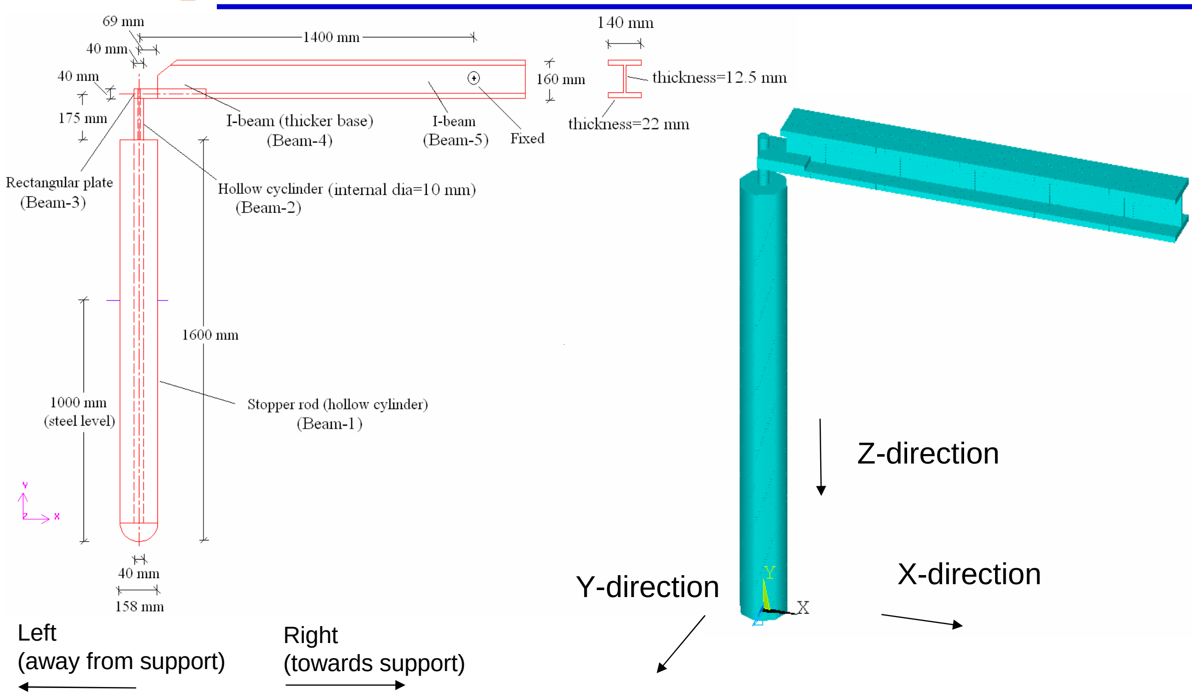
Project Overview

- Static stress analysis on stopper rod system has been carried using ANSYS.
- Two forces have been considered on stopper rod,
  (1) vertically distributed load
  (Drag force, due to tundish velocity)
  (2) Buoyancy force (upward)
- Effect of direction and change in velocity on the stopper tilt has been analyzed.
- FLUENT has been used to model the effects of stopper rod tilt on asymmetry of the steel flow in the nozzle and its outlet ports.

Stopper rod system



Schematic of the stopper rod system

Buoyancy force on stopper rod

- Buoyancy force

Buoyancy force = $(\rho_{steel} - \rho_{stopper\ \ rod})Vg$

Where, $V = \frac{\pi}{4} d^2 L + 0.5 \frac{4}{3} \pi \left(\frac{d}{2}\right)^3$ $\quad d$ is the diameter of stopper rod

$L = L_o - 0.5d$ $\quad L_o$ is the level of steel up to which stopper rod is submerged

$$\rho_{stopper\ \ rod} = 2700 \quad kg/m^3$$

For $L_o = 1m$, **Buoyancy force =808 N**

Drag forces on stopper rod

- Drag force

Drag force is defined as; Drag force= $C_D \frac{1}{2} \rho U_\infty^2 d$

Where, C_D is the drag coefficient, ρ is the density of the steel = 7020 kg/m³.

U_∞ is the free-stream velocity, d is the diameter of the stopper rod

Assume typical cross-flow velocity in tundish, $U_\infty = 0.3 m/s$

$$\mathrm{Re}_D = \frac{\rho d U_\infty}{\mu}$$

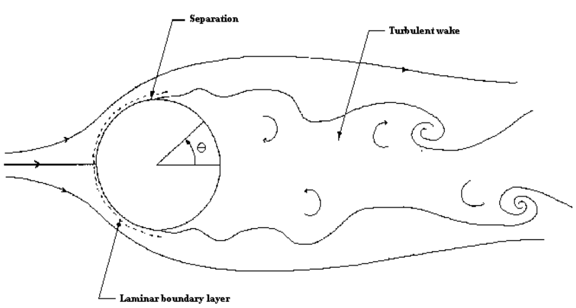
For this velocity, and viscosity $\mu = 0.00669708 \ Ns/m^2$ $\mathrm{Re}_D = 50{,}000$

C_D is about 1.25.(Fig-3, on next slide)

Velocity (m/s)	Drag force (N/m)
0.1	7
0.2	28
0.3	63

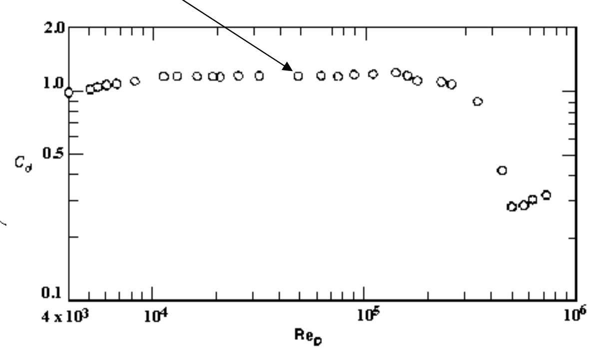
Table-1 drag force as a function of velocity

Drag coefficient



Sub-critical Reynolds number

C_D = 1.25



Basic features of the flow past a circular cylinder

Drag coefficient on a circular cylinder as a function of Reynolds number

Willian J. Devenport et al (2007)

Static structural analysis

- BEAM188 line elements in ANSYS are used to solve equations.
- Allow 6 degree of freedom.
- Cross-sections corresponding to different parts of geometry for various line elements have been taken into account.
- Structural properties of steel **(Reference http://en.wikipedia.org)**
  (E) Young's modulus of steel=210 GPa
  Poisson's ratio=0.3

Simulated cases

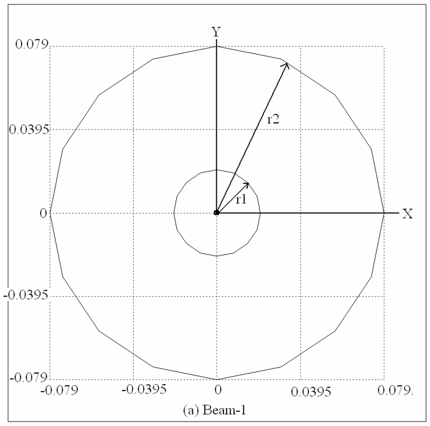
Seven cases have been modelled using ANSYS

Case No	Drag force direction	Velocity (m/s)	Buoyancy
1	Left to right	0.1	Yes
2	Left to right	0.3	Yes
3	Right to left	0.1	Yes
4	Right to left	0.3	Yes
5	Back to front	0.1	Yes
6	Back to front	0.3	No
7	Back to front	0.3	Yes

Cases considered

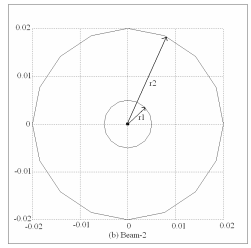
Stopper rod cross sections for Beam Analysis

158mm-OD and 41 mm-ID Stopper Rod (**Beam 1**)



(a) Beam-1

40mm-OD and 10 mm-ID Connecting Rod (**Beam 2**)



(b) Beam-2

cross-section area

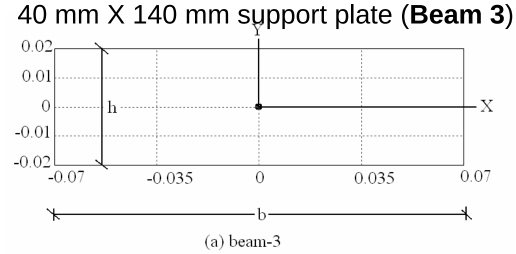
$$A = \pi\left(r_2^2 - r_1^2\right)$$

moment of inertia through centroid

$$I_{xx} = I_{yy} = \frac{\pi}{4}\left(r_2^4 - r_1^4\right)$$

Horizontal Support beam cross-sections for beam analysis

40 mm X 140 mm support plate (**Beam 3**)



(a) beam-3

b=140mm
h=40mm

cross-section area

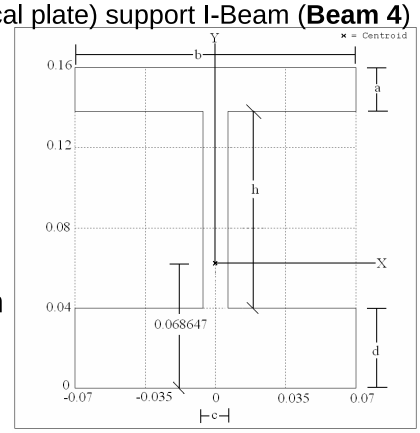
$$A = bh$$

moment of inertia through centroid

$$I_{xx} = \frac{bh^3}{12} \qquad I_{yy} = \frac{b^3h}{12}$$

160 mm X 140 mm (base 40, top 22, 12.5 mm vertical plate) support **I**-Beam (**Beam 4**)

a=22mm
b=140mm
c=12.5mm
d=40mm
h=98mm



(b) Beam-4

cross-section area

$$A = ab + db + hc$$

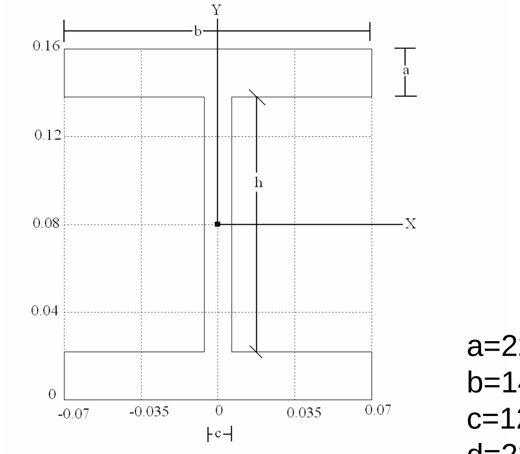
moment of inertia through centroid

$$I_{xx} = ab\left(\frac{a}{2} + h + d - 0.0623\right)^2 + bd\left(0.0623 - \frac{d}{2}\right)^2 + \frac{c(h)^3}{12} + ch\left(\frac{a+h+d}{2} - 0.0623\right)^2$$

$$I_{yy} = \frac{a(b)^3}{12} + \frac{d(b)^3}{12} + \frac{hc^3}{12}$$

Beam Analysis (Cont.)

160 mm X 140 mm support I-Beam (**Beam 5**) (top and base plate 22 mm, vertical 12.5 mm)



(a) Beam-5

cross-section area

$$A = 2ab + hc$$

moment of inertia through centroid

$$I_{yy} = \frac{2ab(b)^2}{12} + \frac{hc^3}{12} \quad I_{xx} = 2ab\left(\frac{h}{2} + \frac{a}{2}\right)^2 + \frac{ch^3}{12}$$

a=22mm
b=140mm
c=12.5mm
d=22mm
h=116mm

Beam Analysis (Cont.)

Beam	Area (m^2)	Area moment of inertia		Torsion constant
		I_{xx} (m^4)	I_{yy} (m^4)	
Beam-1 (Circular hollow cross-section)	0.018272	0.304E-04	0.304E-04	0.608E-04
Beam-2 (Circular hollow cross-section)	0.001177	0.125E-06	0.125E-06	0.250E-06
Beam-3 (Plate with rectangular cross-section)	0.0056	0.747E-06	0.915E-05	0.253E-05
Beam-4 (I-Beam cross-section, thicker base)	0.009905	0.355E-04	0.142E-04	0.320E-05
Beam-5 (I-Beam cross-section)	0.00761	0.312E-04	0.101E-04	0.106E-06

Area moment of inertia and torsion constant for various beams

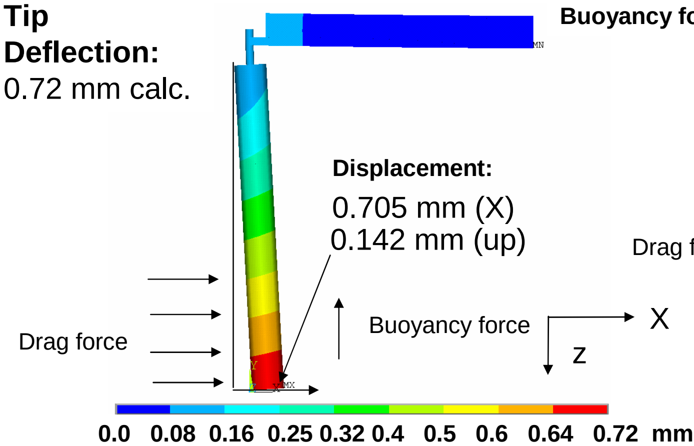
Flow from left to right with buoyancy

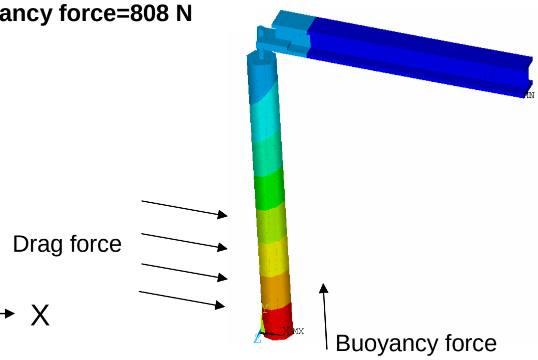
Drag=63 N/m (Tundish velocity=0.3 m/s),

Buoyancy force=808 N

(Case-2)

Tip Deflection:
0.72 mm calc.





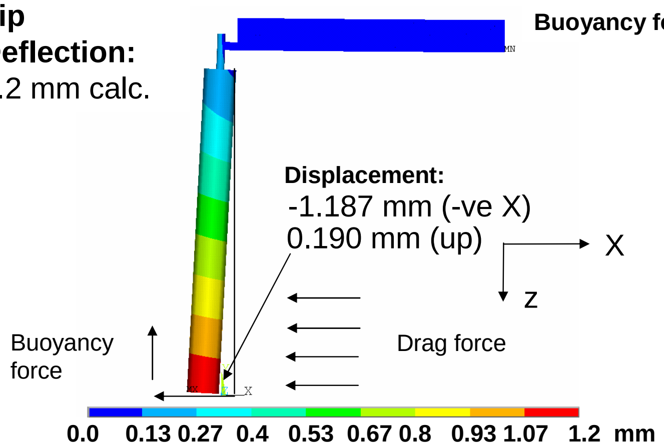
Drag force try to tilt the stopper in +ve X- direction, and buoyancy in the upward direction, this way these forces act against each other and deformation is smaller

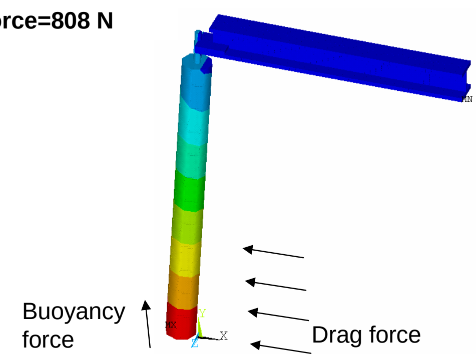
Flow from right to left with buoyancy

Drag=63 N/m (Tundish velocity=0.3 m/s),

Buoyancy force=808 N

Tip Deflection:
1.2 mm calc.





Drag force try to tilt the stopper in -ve X- direction, and buoyancy in the upward direction, and they act in favor, this results in higher deformation compared to previous case

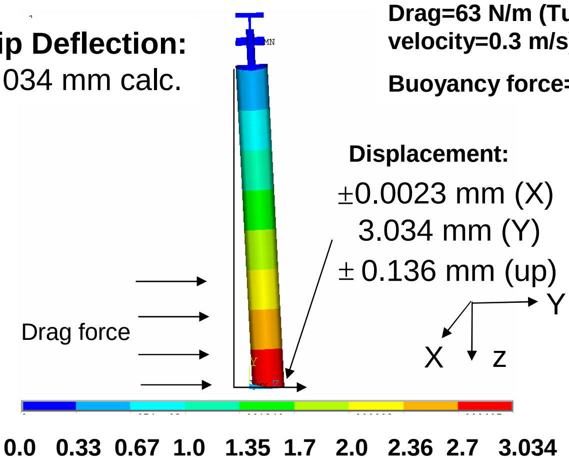
Cross-flow without Buoyancy

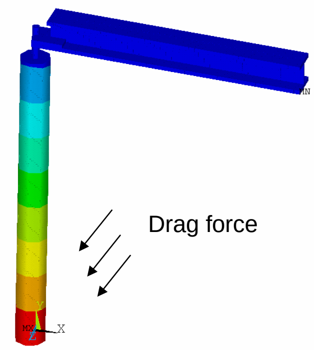
Tip Deflection:
3.034 mm calc.

Drag=63 N/m (Tundish velocity=0.3 m/s),

Buoyancy force=None

Displacement:
±0.0023 mm (X)
3.034 mm (Y)
± 0.136 mm (up)





Drag force try to tilt the stopper in +ve Y- direction

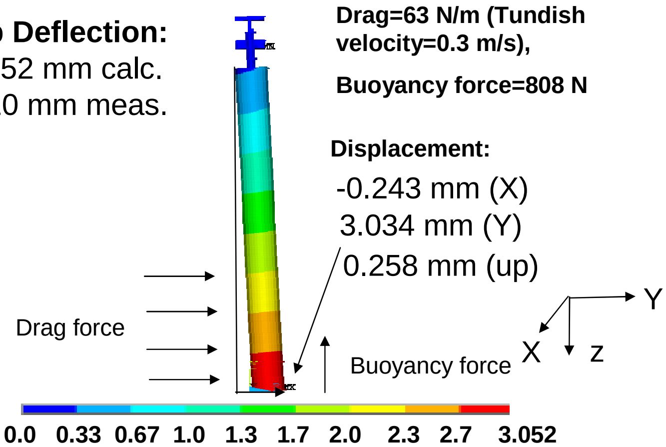
Cross-flow with Buoyancy

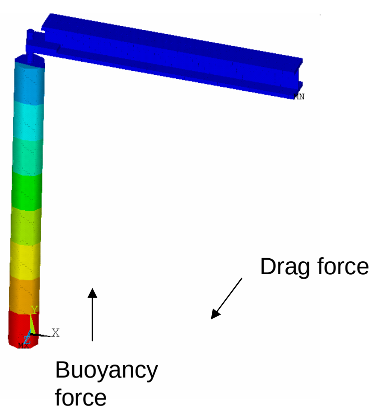
Tip Deflection:
3.052 mm calc.
6-10 mm meas.

Drag=63 N/m (Tundish velocity=0.3 m/s),

Buoyancy force=808 N

Displacement:
-0.243 mm (X)
3.034 mm (Y)
0.258 mm (up)





Drag force try to tilt the stopper in +ve Y- direction, and buoyancy in the upward direction. Deformation is slightly higher than previous case because horizontal beam is stiffer for vertical deformation compared to torsion

Displacements

Case	x-displacement	y-displacement	z-displacement	Total displacement magnitude
Flow from left to right (0.1 m/s) with buoyancy **(Case-1)**	-0.137 mm(max)	0	0.126 mm(max)	0.186 mm(max)
Flow from left to right (0.3 m/s) with buoyancy **(Case-2)**	0.705 mm(max)	0	0.142 mm(max)	0.719 mm(max)
Flow from right to left (0.1 m/s) with buoyancy **(Case-3)**	-0.345 mm(max)	0	0.139 mm(max)	0.372 mm(max)
Flow from right to left (0.3 m/s) with buoyancy **(Case-4)**	-1.187 mm(max)	0	0.190 mm(max)	1.202 mm(max)
Flow from back to front (0.1 m/s) with buoyancy **(Case-5)**	-0.241 mm(max)	0.334 mm(max)	0.140 mm(max)	0.435 mm(max)
Flow from back to front (0.3 m/s) without buoyancy **(Case-6)**	± 0.0023 mm(max)	3.034 mm(max)	±0.136 mm(max)	3.037 mm(max)
Flow from back to front (0.3 m/s) with buoyancy **(Case-7)**	-0.243 mm(max)	3.034 mm(max)	0.258 mm (max)	3.052 mm(max)

Table-4 Deflections for various cases considered

Conclusions on static structural analysis of stopper rod system

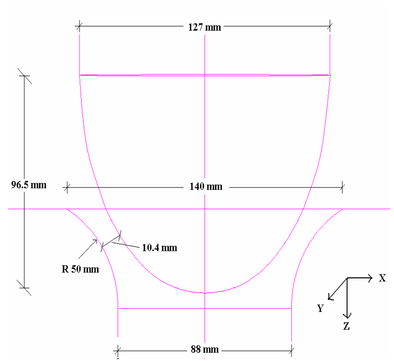
- A model of deflection of a stopper rod has been developed that includes the effects of buoyancy of the low-density stopper, and the drag force from fluid flow in the tundish.
- Stopper tip bends in direction of tundish flow, and slightly upward. Max deflection is at stopper tip. Deflection is governed mainly by the tiny connection rod, (beam 2) as stopper itself bends very little.
- Transverse deflection (in y-direction) is much larger, owing to small tortional moment / stiffness of the horizontal support beam (5).   Thus, tundish cross-flow appears to be the main cause of stopper deflection.
- Drag force from tundish velocity is much more important on tip deflection than upward buoyancy force on stopper rod (even though the drag force is much smaller in magnitude).

Conclusions on static structural analysis of stopper rod system

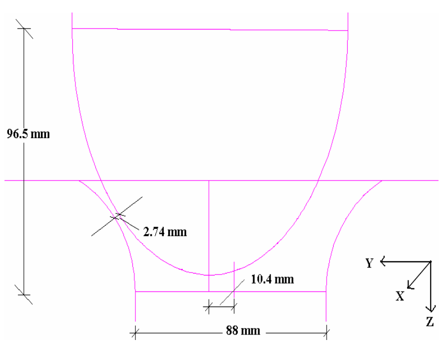
- Increasing velocity greatly increases deflection (square relationship, owing to effect on drag force)
- Measurements at POSCO estimate displacement at the bottom of stopper rod is 6-10 mm in transverse (y) direction (perpendicular to direction of stopper support).
- Calculated displacements are appear to be smaller than measured, perhaps due to
  - neglect of play in the joints.
  - thermal distortion, and measurement problems
  - Neglect of play and deflection of the vertical assembly that supports and moves the stopper rod

Effect of stopper tip deflection on asymmetric flow in the nozzle

- Fluent has been used to simulate 3-D turbulent steel flow in a nozzle with a tilted stopper rod.



Aligned Stopper



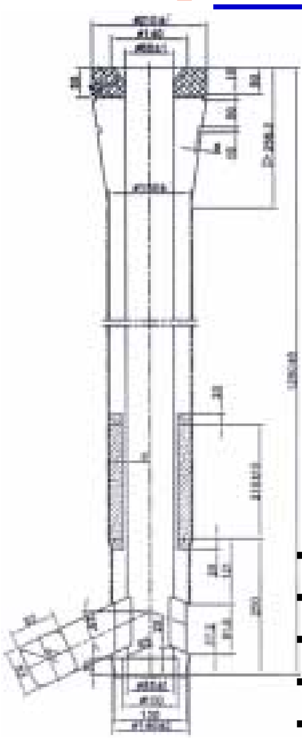
Misligned Stopper

Effect of the stopper rod tilt on nozzle flow

- Hexahedral mesh has been generated in 3-Dimensional computational domain in GAMBIT.
- Turbulence has been modeled using standard k-epsilon model.
- 50% open flow area (minimum gap=10.4 mm) has been considered before tilting the stopper rod in the flow domain.
- A cylinder of diameter 540 mm and 500 mm height has been created to partially model tundish flow for the inlet conditions.
- Uniform velocity inlet conditions are applied on the circumference and the top of this cylinder based upon a typical casting speed (1.56 m/min, 65.14 kg/s steel flow) and slab dimensions (250 mm X 1430 mm).

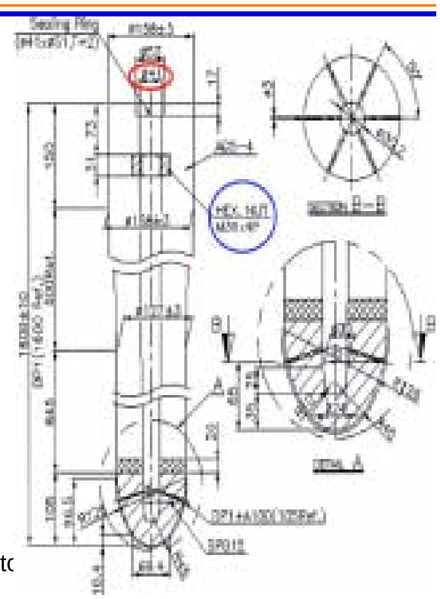
- Two cases have been considered.
  Case-1: stopper rod is tilted 10 mm in +ve y-direction (Towards NF)
  Case-2: Stopper rod is tilted 10 mm in -ve x-direction (Towards EF)

Nozzle Geometry



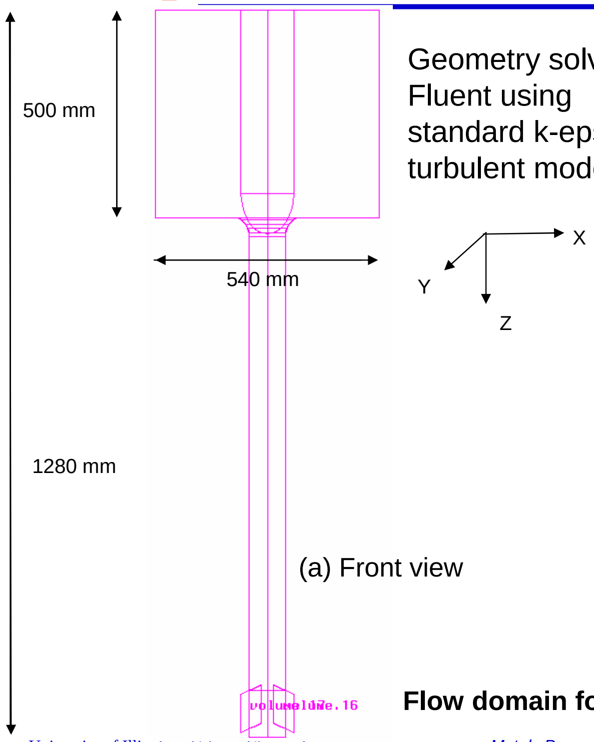
SEN and stopper rod

at Gwangyang works POSCO

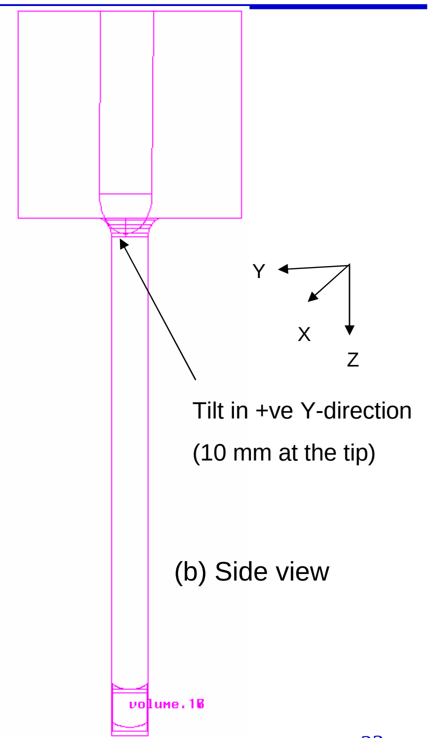


- Height of the nozzle 1280 mm from top to bottc
- Bore diameter of nozzle 88 mm
- Outlet port cross-section 83 mm X 83 mm
- Angle of outlet port from horizontal 25^{o}
- Stopper rod diam 127 mm till ~ 1000 mm

Physical Domain (Case-1)

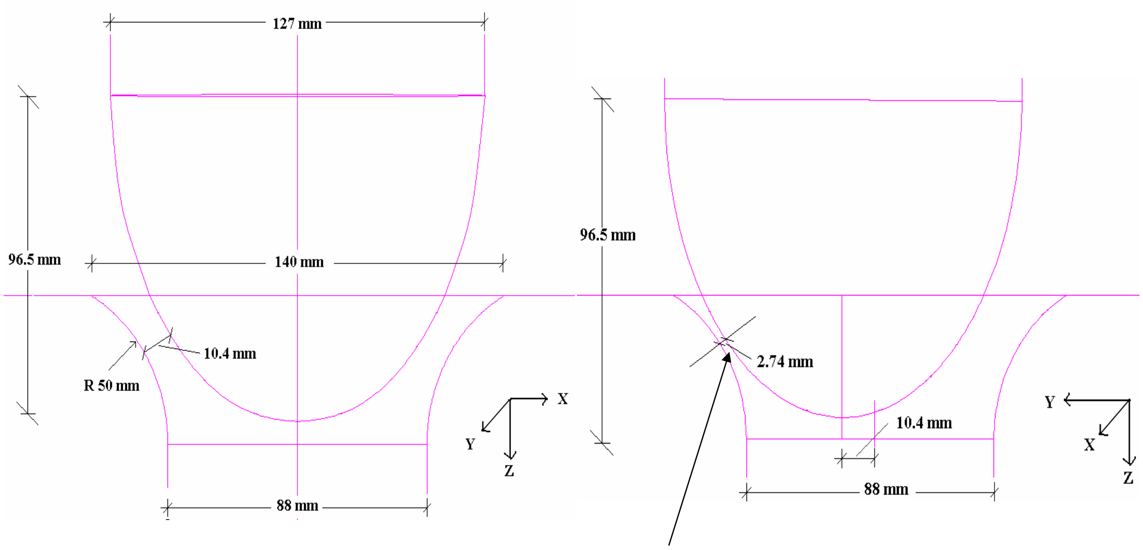


Geometry solved in Fluent using standard k-epsilon turbulent model



Flow domain for Case-1

Effect of tilt on flow area close to UTN (Case-1)



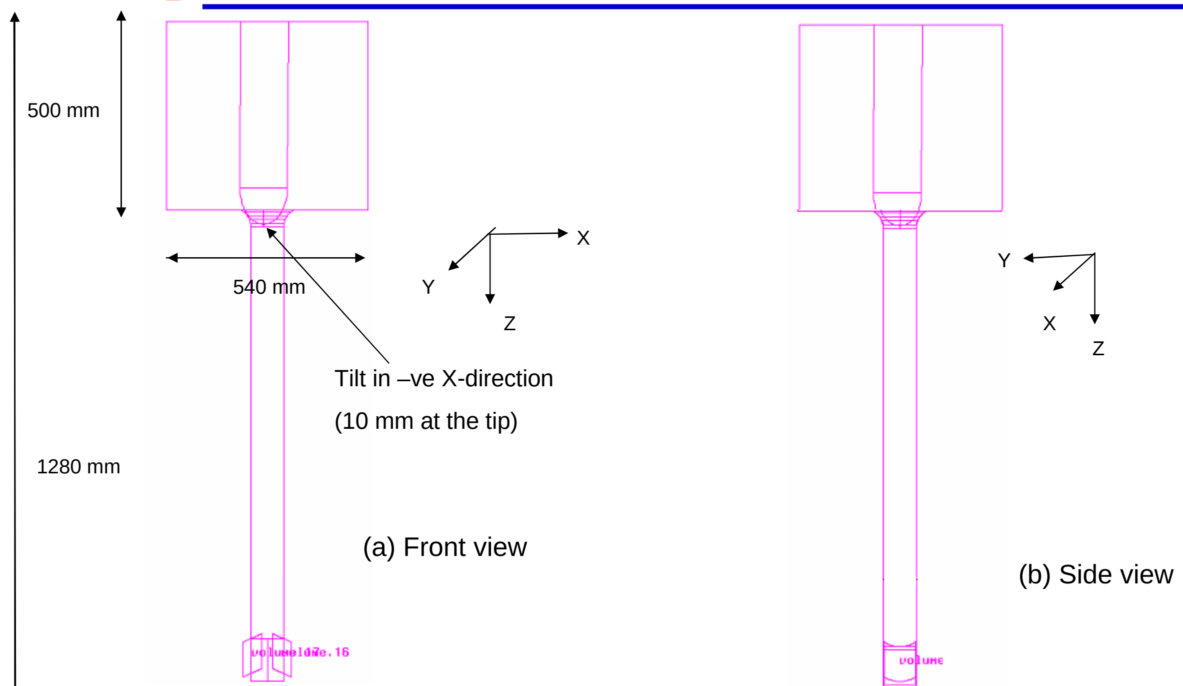
•Initial gap=10.4 mm

•Gap (2.74 mm) after the tilt in Y-Z plane

Front view **Side view**

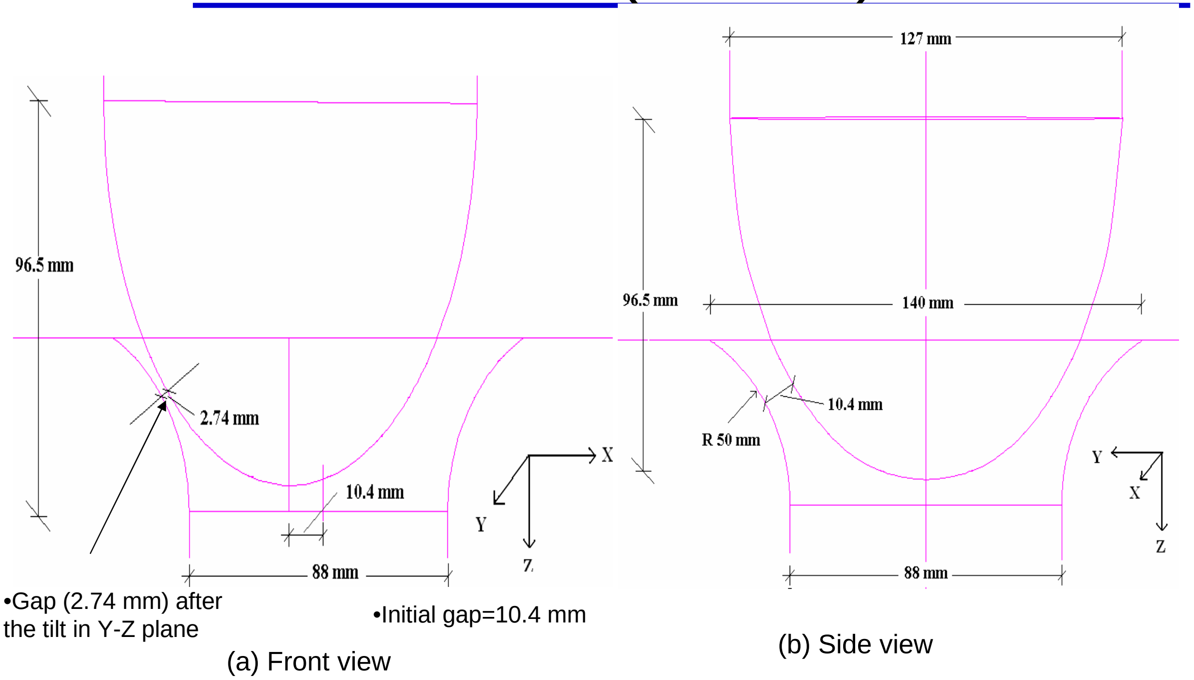
Geometry around UTN and stopper rod tilt with 50% flow area

Physical Domain (Case-2)



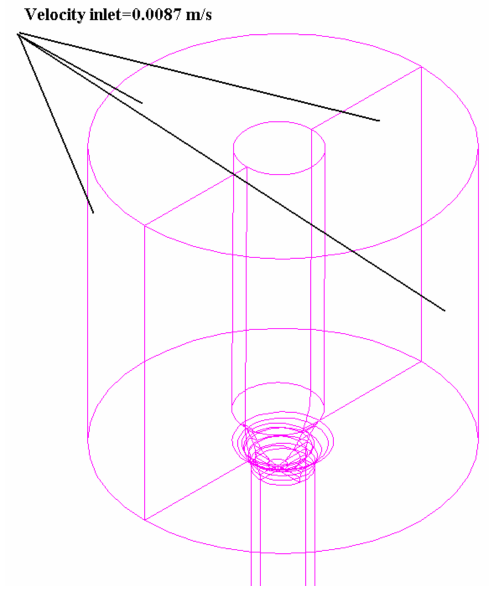
Flow domain for Case-2

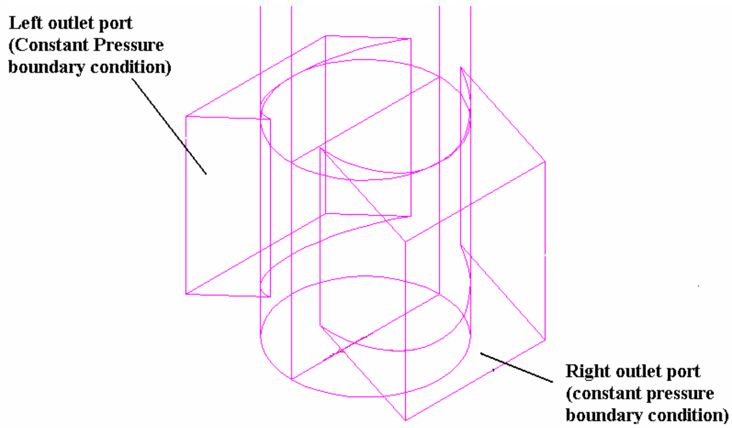
Effect of tilt on flow area close to UTN (Case-2)



Geometry around UTN and stopper rod tilt with 50% flow area

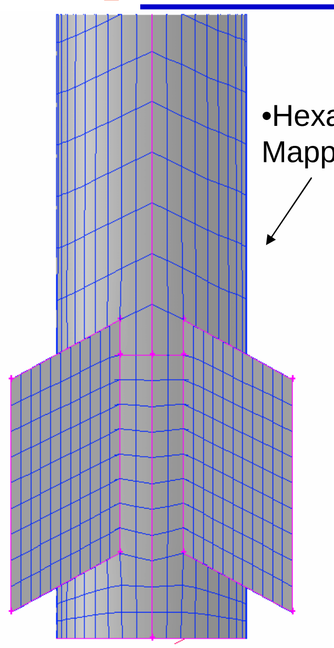
Boundary conditions





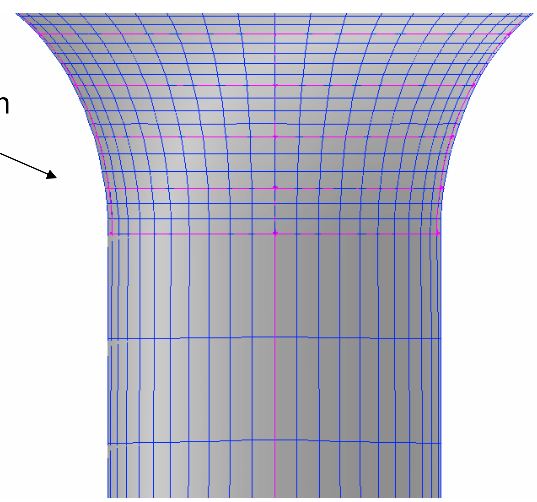
•All other boundary conditions are taken wall.

Mesh in the flow domain



•Hexahedral Mapped mesh

Outlet port (Front view)

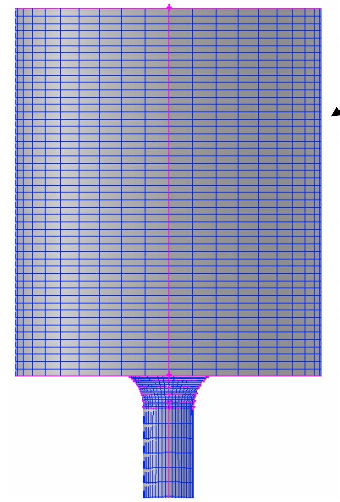


UTN (Front view)

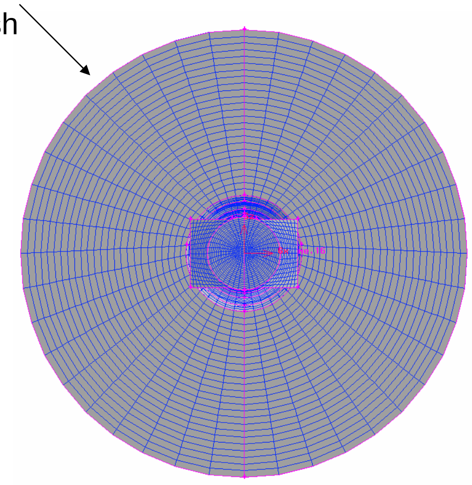
Mesh around UTN and at outlet port

Mesh in the flow domain

•Hexahedral Mapped mesh



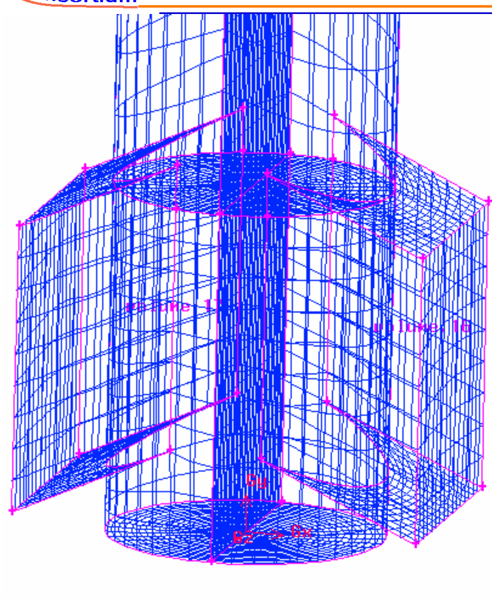
UTN and cylinder in tundish (Front view)



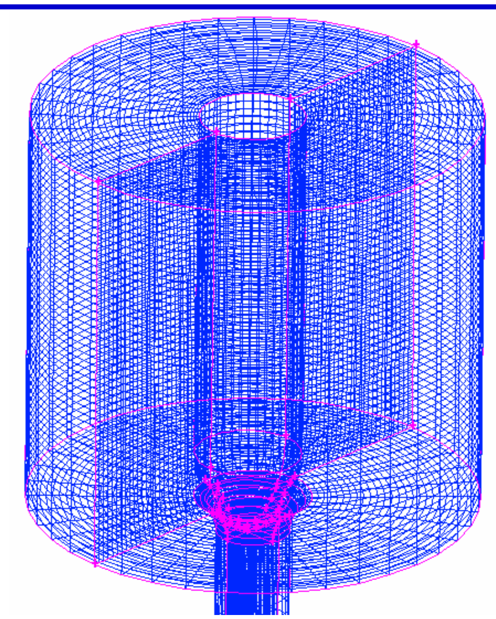
Top view of the flow domain

Mesh in the flow domain

Internal mesh in the flow domain



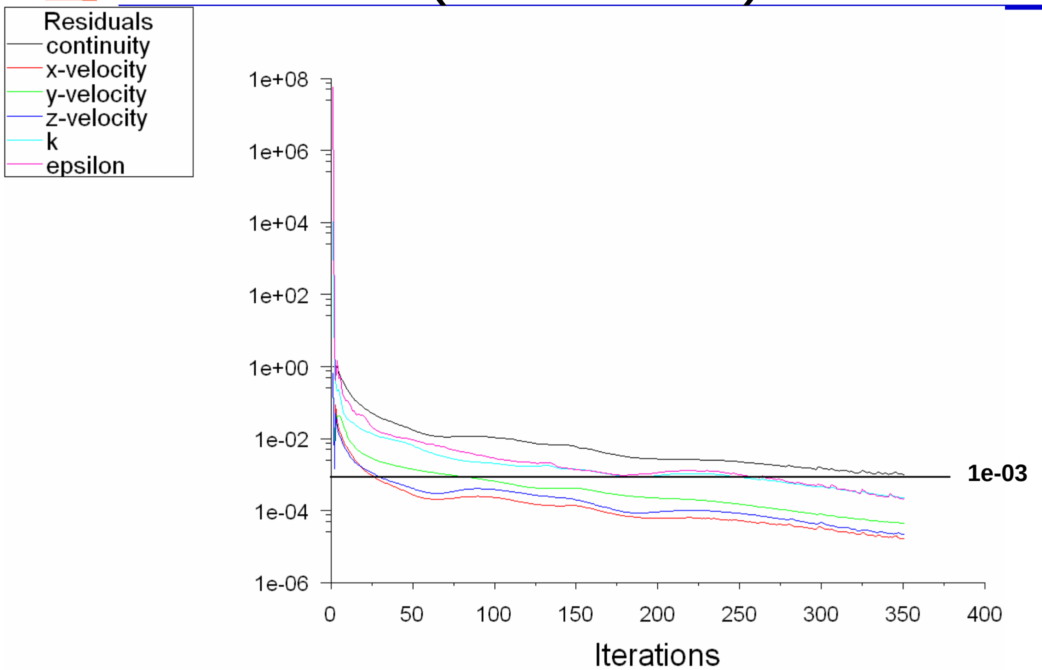
Outlet ports mesh



Mesh in the top domain
(isometric view)

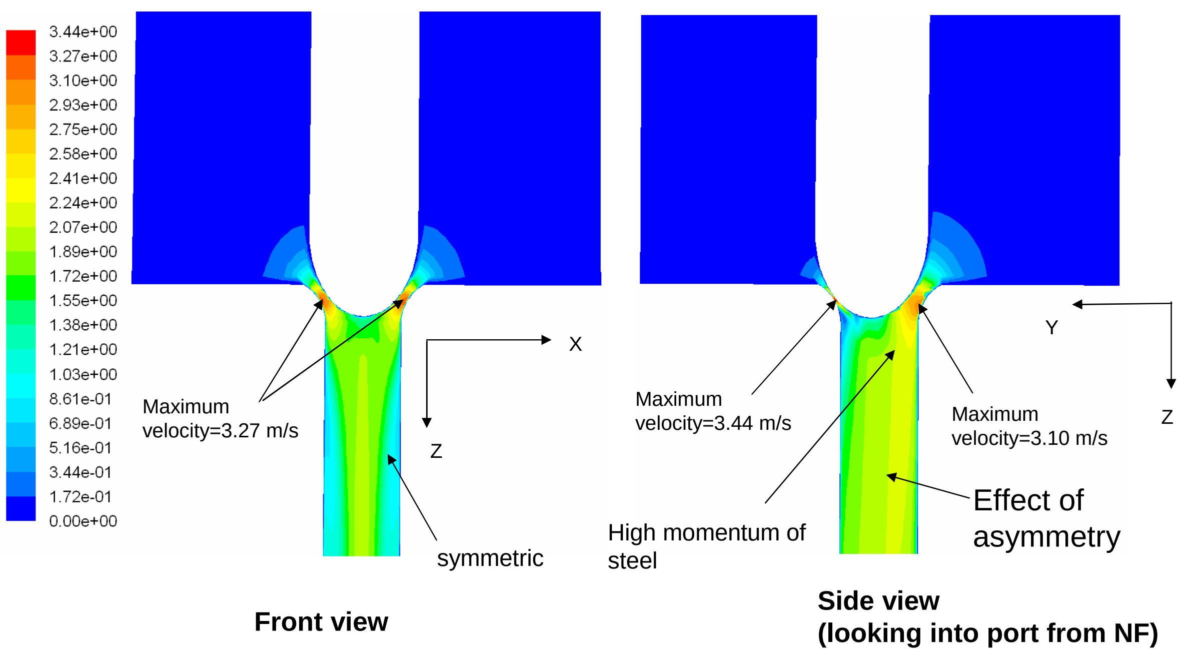
Internal mapped hexahedral mesh

Convergence (Case-1) (Residuals)



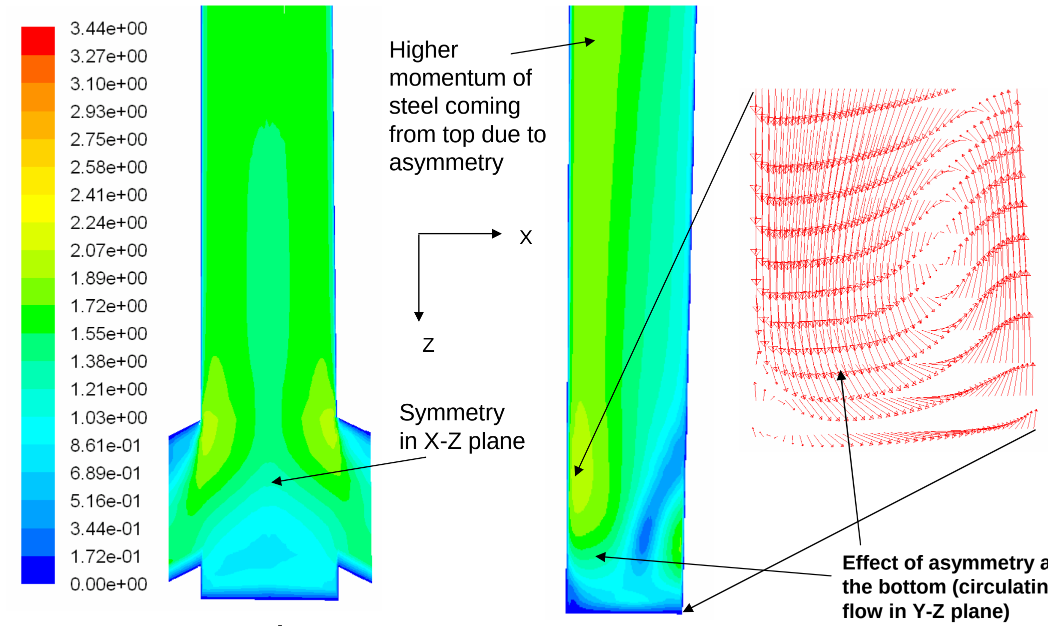
Residuals and convergence criterion for Case-1

Velocity contours in the top region (Case-1)



Velocity magnitude contours in the top region

Velocity at the bottom of the domain

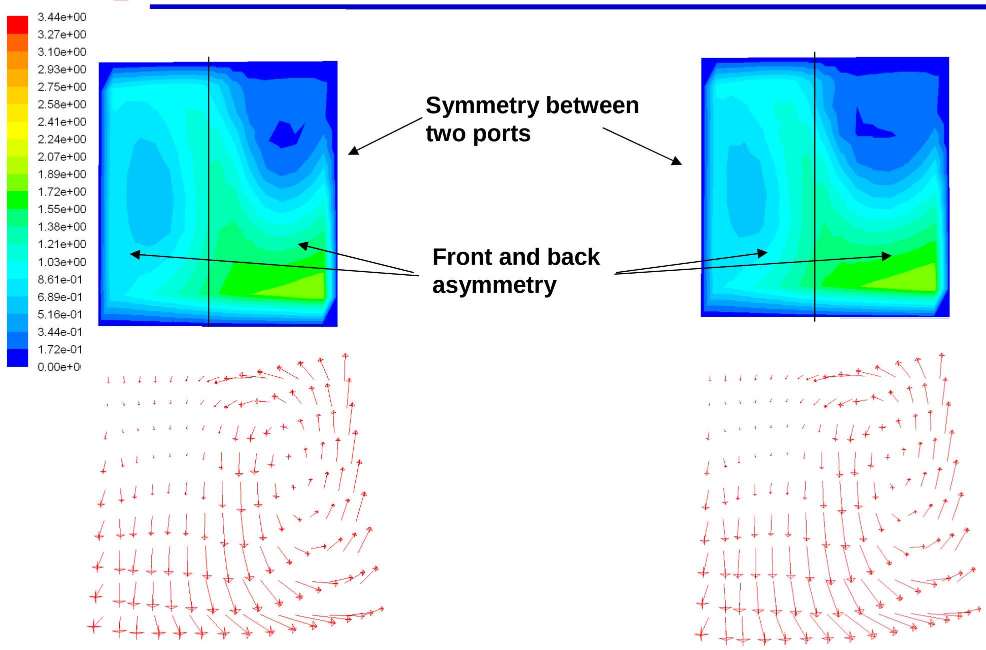


Front view

Side view

Velocity magnitude contours in the nozzle close to the outlet ports

Velocity at outlet ports (Case-1)



Left outlet port

(Mass flow rate=32.91 kg/s)

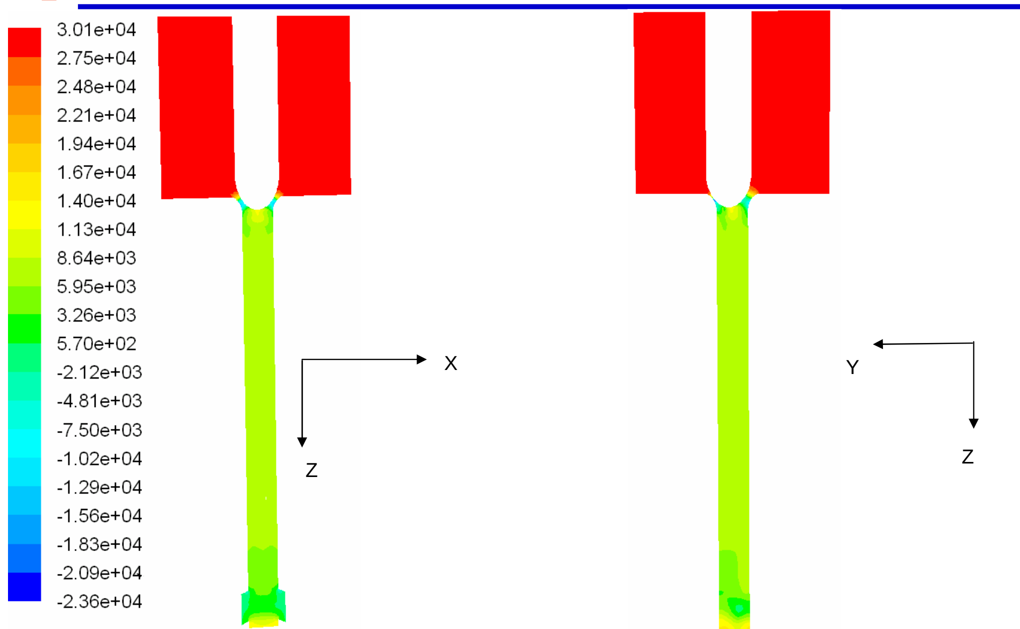
Velocity magnitude

contours on outlet ports

Right outlet port

(Mass flow rate=32.23 kg/s)

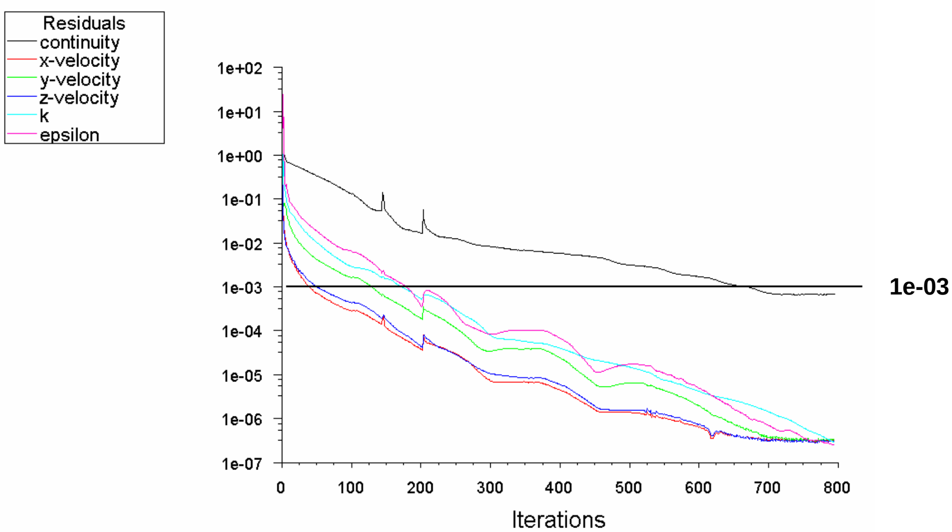
Results (Case-1) (Cont.)



Front view **Side view**

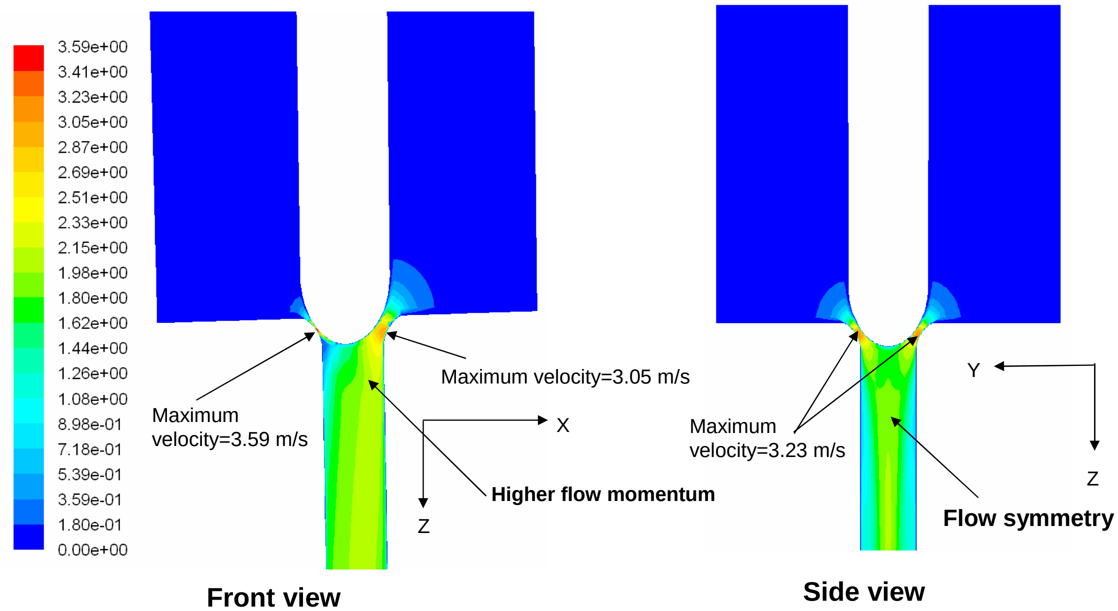
Pressure contours in the whole domain

Convergence (Case-2) (Residuals)



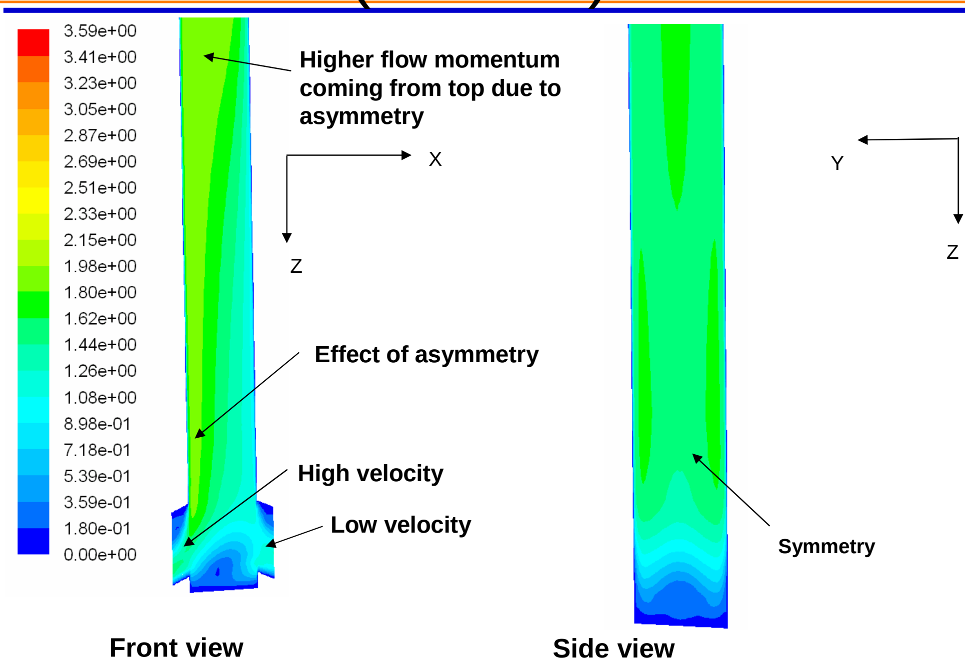
Residuals and convergence criterion for Case-2

Velocity contours in the top of the flow domain (Case-2)



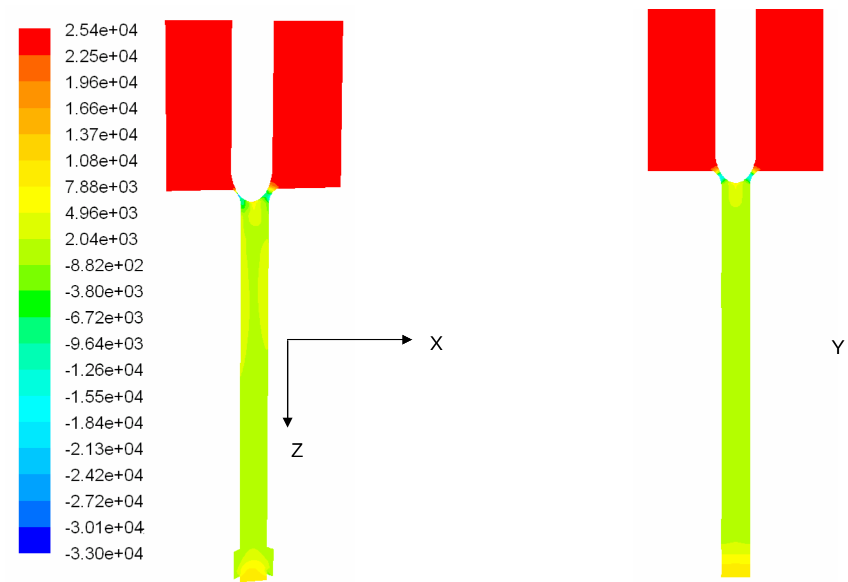
Contours of velocity magnitude in the top region at the centre line

Velocity contours at the bottom (Case-2)



Velocity contours in the nozzle close to the outlet ports

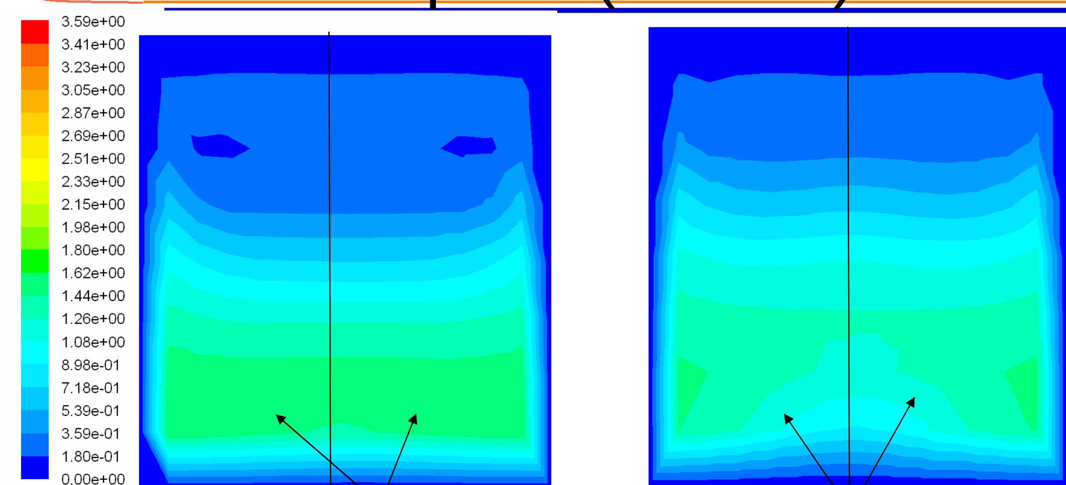
Pressure contours in the whole domain (Case-2)



Front view **Side view**

Pressure contours in the whole domain

Velocity contours at the outlet ports (Case-2)



Effect of asymmetry, high velocity at the bottom compared to right outlet port

Front and back symmetry in both ports

Left outlet port

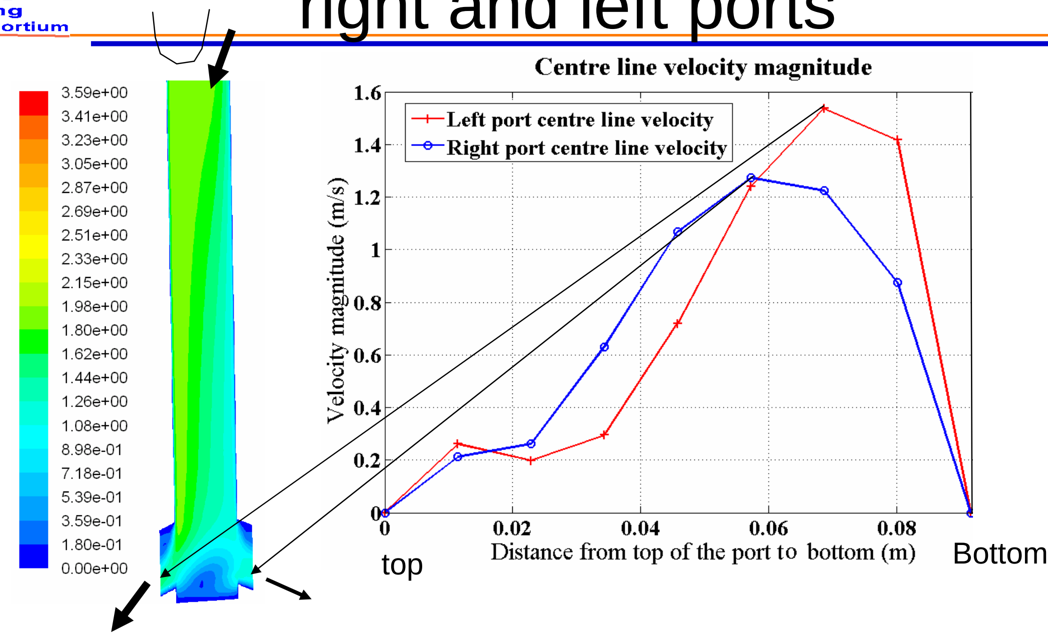
(34.57 kg/s)

Right outlet port

(30.57 kg/s)

Velocity contours on outlet ports

Centre line velocity magnitude in right and left ports



More flow
Steeper downward

less flow
Shallower jet angle

Conclusions on flow modelling

- Steel flow has been modelled in POSCO nozzle with domain modified according to a 10-mm deflected stopper rod.

- In case-1, (Y-direction tip deflection), flow from the outports is symmetric (left and right), however within a single port front and back asymmetry exists. Significant asymmetric flow in the mold is directed towards the wideface in the opposite direction of the stopper tip deflection.

- In case-2, (-X-direction tip deflection), the jet is centered towards the NFs, but the flow is asymmetric between the two ports, more flow (53%) exits the right port towards the NF in the direction of the stopper tip deflection.

Conclusions on flow modelling

- In Case-1, velocity is maximum at the bottom and backside of the outlet ports.
- In Case-2, velocity and flow rate is higher at the outlet port opposite to the higher gap at UTN, which is due to higher momentum from the top.
- Reverse flow has been found in both cases at the top of the outlet port.

Final conclusions

- From the static structural analysis, cross flow has been found producing maximum deformation at the tip of the stopper rod.
- Drag force is more crucial in deformation.
- Cross-flow/cross-deformation does not generate asymmetry between the two ports, but gives front and back asymmetry within same port.
- Although, front/back deformation is small, but has considerable effect on the flow asymmetry between two ports.
- Velocity is higher at the bottom of the outlet port opposite to the higher gap at UTN.

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